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Chromatic Display of Digital Weather Data

Jeannine V. Lamar and Roy H. Stratton

A Report prepared for
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



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PREFACE

A few years ago, it became apparent that man's expanding technology could have side effects that might seriously alter the climate. Realizing the potential danger and noting the lack of appropriate research, the (then) Advanced Research Projects Agency initiated a climate dynamics study at Rand in 1969. In this study, a global circulation model is used to simulate the climate numerically. In addition, Rand has for the last several years been developing photographic and computer methods of image enhancement. One of many possible applications of these methods could be an improved display of meteorological data as an aid to interpretation of output from the model. This report is a preliminary investigation of that application.

The following Rand reports have provided direct inputs to the present work:

R-877-ARPA *A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model*

R-787-NIH *Computer Techniques for Pseudocolor Image Enhancement*

R-597-PR *A Photographic Technique for Image Enhancement: Pseudocolor Two Separation Process*

R-596-PR *A Photographic Technique for Image Enhancement: Pseudocolor Three Separation Process*

SUMMARY

The global circulation model of the Rand Climate Dynamics Study is briefly described. The present method of interpretation of data from this program is discussed; in many cases the hard copy is difficult to interpret because the lines defining the contour intervals overlap, coincide, and become indistinguishable. Some possible alternative or complementary techniques using both pseudocolor and false color for display of these data are presented, in which digital data are transformed to black-and-white intermediate film strips and subsequently combined to produce color images. A method of testing our new techniques to determine their merit is suggested.

CONTENTS

Preface.....	.....
Summary.....	.....
Section	
I. BACKGROUND.....	.....
Purpose of Climate Dynamics Project.....	.....
Present Interpretation of Climate Data.....	.....
Image Generation and Display.....	.....
II. METEOROLOGICAL DATA IN COLOR.....	.....
III. TECHNIQUES.....	.....
Generation of Data on 35-mm Film.....	.....
Presentation of Data in a Color Format.....	.....
IV. CONCLUDING REMARKS.....	.....
REFERENCES.....	.....

I. BACKGROUND

PURPOSE OF CLIMATE DYNAMICS PROJECT

The Rand/ARPA Climate Dynamics Project is directed toward the formulation of a theory of climatic change. One of the major tools of the project is numerical simulation of climate with a general circulation model. The original program⁽¹⁾ was developed by Professors Mintz and Arakawa in the 1960s with support from NSF. It has since been modified and updated by members of the Climate Dynamics Group at Rand. The model is run with input conditions reflecting present climatic variables or conditions reflecting man-made changes or past climates. Various experiments are performed with this model, such as the comparison of simulations with observed weather data and comparisons among the various simulations themselves. This has generated research in data handling and analysis. A program of meteorological research is aimed at increasing the fidelity of the model and understanding the results of the simulations.

PRESENT INTERPRETATION OF CLIMATE DATA

The global circulation model uses a grid over the earth of 72 five-degree divisions of longitude and 46 four-degree divisions of latitude. A given set of initial and boundary conditions is input to the program. It then calculates the global weather conditions by integrating the primitive equations of motion of the climatic variables over a specified period and stores the data for each desired climatic variable.

The model is relatively sophisticated in its treatment of the physics of large-scale atmospheric motion, and the method of numerical solution is quite complex. Some simulation runs take as many as 25 to 30 hours of IBM 360/91 time. Storage and retrieval systems are built in to circumvent both program and machine failure, so that a simulation can be restarted part way through its calculation.

A Fortran program, written by A. B. Nelson of Rand, accesses these data and generates a series of Integrated Graphics System⁽²⁾

subroutines, which in turn create input to a microfilm plotter for generation of the weather maps. These maps show the contour intervals of such variables as temperature, pressure, and precipitation in addition to the continental outlines.

Figure 1 is one of these maps. It is a plot of total cloudiness averaged over a 30-day period from one of the experiments. This map is drawn with only two contour intervals: the solid line denotes 0-percent cloud cover and the dashed line denotes 50-percent cloud cover. It also contains the relative highs and lows of the cloudiness of adjacent areas, and is plotted over a background of the continental outlines, which are also shown as solid lines.

If the parameter to be plotted varies considerably over a small area or if the number of contour intervals to be drawn is greater than 10, the map contains so many lines as to make it almost impossible to interpret. Figure 2 is an example of one of these maps. The same variable, total cloudiness, is plotted here as in Fig. 1, but the contour interval is .05.

This example demonstrates the difficulty in following the contour intervals or establishing the location of the highs and lows. When a comparison between two maps of the same parameter (plotted over different time ranges) or between two maps of different parameters is desired, the difficulty in interpretation is compounded. Up to the present time, no attempt has been made to plot two parameters on one map -- primarily because of the expected confusion of two sets of contour intervals and two sets of highs and lows.

IMAGE GENERATION AND DISPLAY

During the past few years, a group at Rand has been developing methods of image enhancement, including the creation of images in shades of gray on a microfilm plotter, photographic pseudocolor transformation of existing imagery,^(3,4) and various combinations of these techniques.^(5,6)

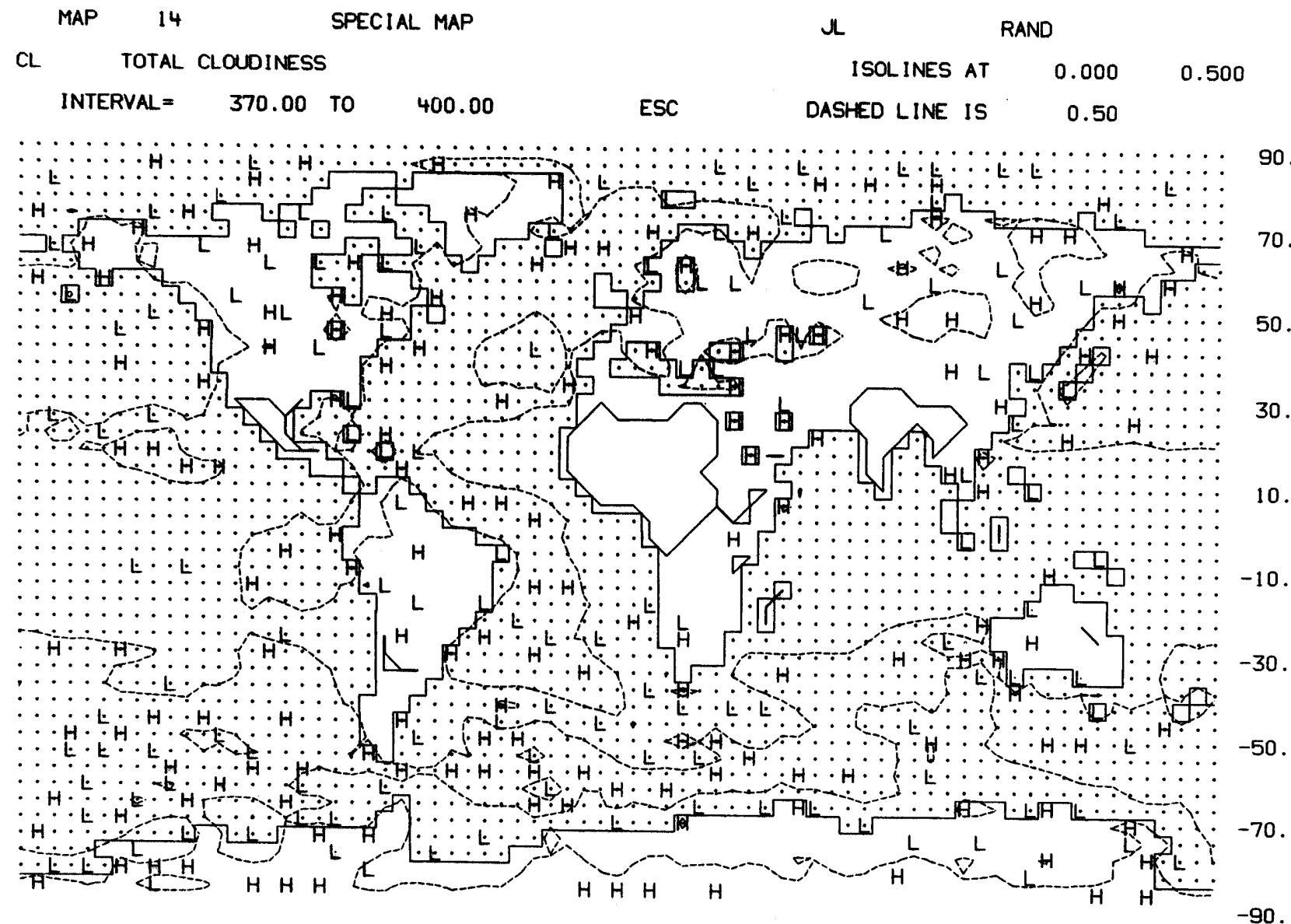


Fig.1 — Map of total cloudiness containing two contour intervals

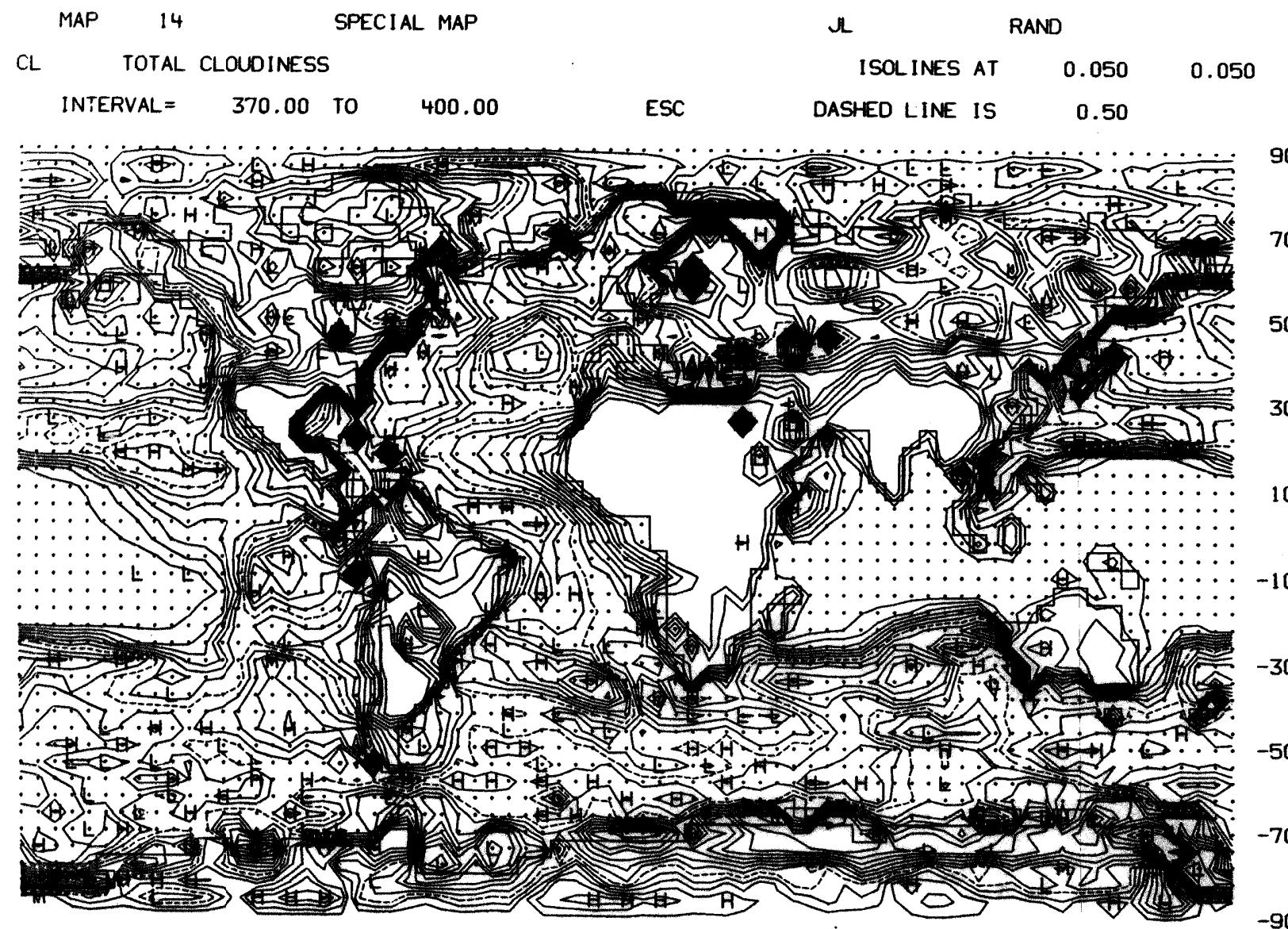


Fig.2 — Map of total cloudiness containing twenty contour intervals

Gray-Scale Image Display

Images in shades of gray are created by a microfilm plotter from digital data. The digital data are in the form of an $n \times n$ matrix whose elements are the numerical representation of the shade of gray to be seen in the image. Thus, the image can be visualized as being composed of a matrix of picture elements (or pixels) where each pixel is a shade of gray. The image is plotted on a cathode-ray tube, pixel by pixel, with each pixel shaded to reflect the digital value in the matrix. The shade of a pixel is determined by the number of lines or vectors which are plotted within the pixel. After the entire image has been created, it is photographed onto 35-mm microfilm.

Colored Image Display

The eye can discriminate only about 15 to 20 shades of gray under a given adaptation level, yet under the same conditions it can discriminate several times that many (hundreds) different colors. Even though a complex image may contain a comparatively small number (10 or less) of discrete density levels, the discrimination or "separation" process of the eye is much more rapid if these densities are transformed into colors. This implies that more information could be extracted in a shorter time through the substitution of color for black and white.

Several systems of color space have been devised for quantifying the visual sensation of color. Variations exist among these systems, but almost without exception the brightness sensation (luminosity) is represented by the vertical axis. The other two dimensions of the color solid can be similar to a polar coordinate system, where the radius R denotes saturation and angle θ denotes hue as in the Munsell system, or they may be expressed in a rectangular coordinate system such as the CIE chromaticity diagram. These systems are discussed at length by the Committee on Colorimetry.⁽⁷⁾ A color solid is shown in Fig. 3 that depicts the relationship between the three variables of hue, saturation, and brightness.

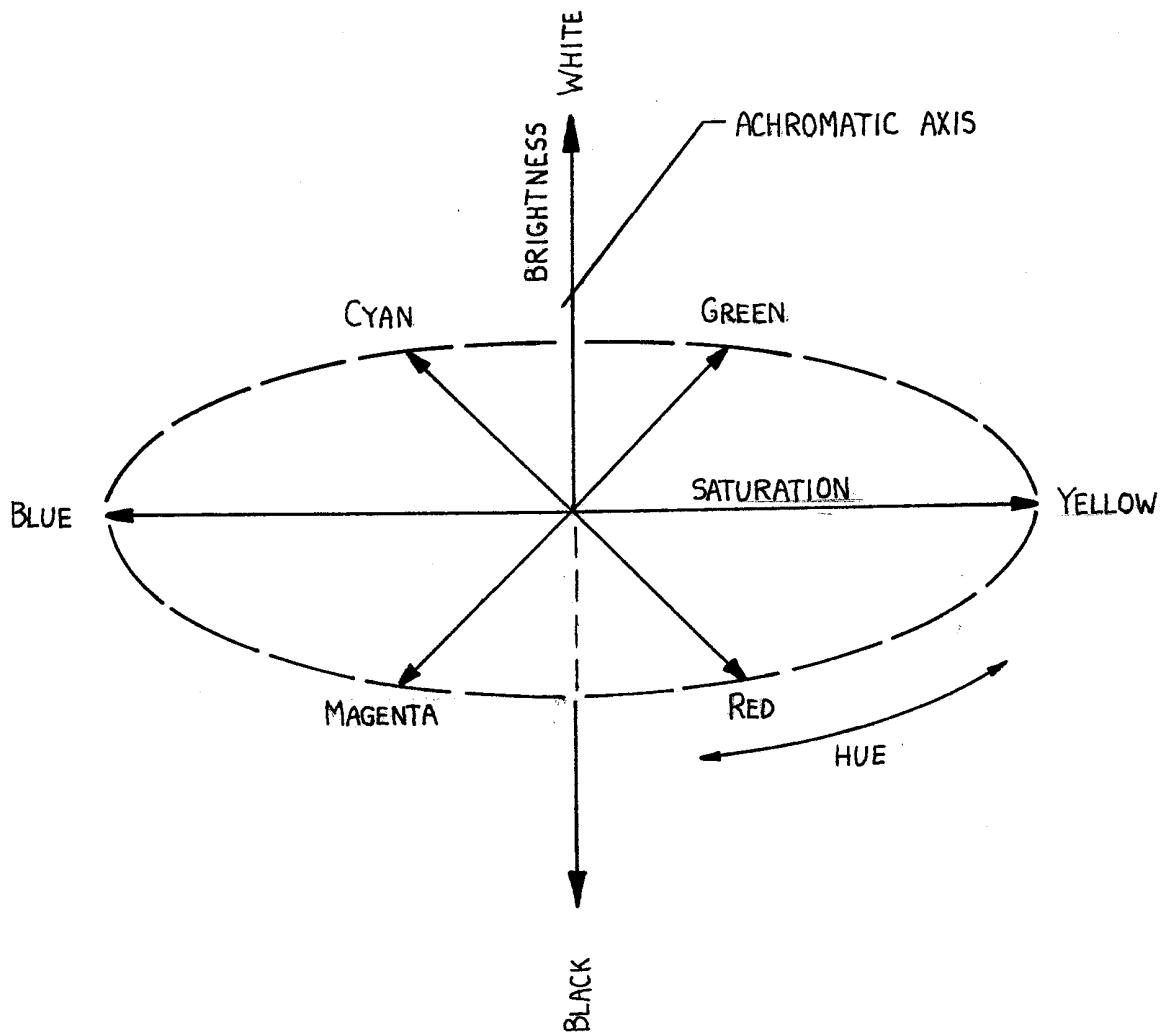


Fig.3 — Color solid showing relationship between hue, saturation, and brightness. Increasing saturation approaches the dashed line. The three additive primaries are red, blue, and green; their complementaries (subtractive primaries) are cyan, yellow, and magenta, respectively

All visual sensations produced by a black-and-white image lie on the vertical achromatic axis of the color solid, since black-and-white images have no saturation or hue. By producing a black-and-white to color image transformation, we have gained access to the other two

dimensions of the solid, thereby exploiting the color discrimination of the eye. However, in presenting black-and-white imagery in color, we must be careful not to confuse the observer. Even though the eye can discriminate more colors than it can shades of gray, a color display would be meaningless were the observer not cognizant of what conditions various different colors represent. The authors believe that this situation could be largely remedied by (1) the use of a color key in each image, and (2) training the observer to use the color key with several images of the same type.

II. METEOROLOGICAL DATA IN COLOR

In presenting meteorological data in color, we plan to use both pseudocolor and false color. Pseudocolor is a simple transformation in which only one parameter is used. As an example, a global temperature map in black and white in which the density change from light to dark represents temperature excursions from high to low could be transformed into an image to contain all the spectral hues in which the high temperatures are presented as red, the medium temperatures as yellow-green, and low temperatures as blue. This transformation is merely a chromatic expansion of the original gray scale which renders a much longer path through the color solid. A false-color presentation involves the use of more than one parameter in the display, such as temperature and precipitation. For example, let us combine our black-and-white temperature map with a precipitation map in which changes of density from light to dark represent precipitation levels from high to low. Let us assume that the temperature map is presented in one color in combination with the precipitation map in the complementary color in such a way that the color of any point on the display lies somewhere on one of the many possible lines (within the color solid) connecting the two primary colors, and that this line intersects the achromatic axis, so some portions of the image could be either white, gray, or black. If the temperature image were presented in red, combined with the precipitation image in cyan (red complementary), by using only three discrete black-and-white levels in each image, the resulting color matrix of the combination would appear as in Fig. 4. This matrix contains nine possible points within the color solid, each representing a different combination of temperature and precipitation. For instance, dark red indicates low precipitation and medium temperature; white indicates high temperature and high precipitation. This is a simple color key with only nine discrete combinations of the two parameters, and when the image is viewed, each of the colors will be clearly defined and easily discriminated. If the black-and-white images each contained, say, 10 density levels, their combination would yield 100

possible colors. While the observer might not be able to single out a specific color from the image, large-scale pattern detection would be possible. We intend to generate imagery in matrices of between 3 and 10 density levels to determine which transformation is most informative without confusing the observer. By taking combinations of two at a time of temperature, precipitation, cloudiness, evaporation, etc., and by using different combinations of primary colors, the number of possibilities becomes large indeed. It is to be hoped that our investigation will indicate which of these combinations are the most helpful to the meteorologist.

Temperature			
Low	Medium	High	
Saturated Cyan	Light Cyan	White	High
Dark Cyan	Gray	Light Red	Medium
Black	Dark Red	Saturated Red	Low

Precipitation

Fig.4 — Matrix showing possible colors for combined presentation of climatic data. Amount of red is a function of temperature and amount of cyan (red complementary) is a function of precipitation.

III. TECHNIQUES

GENERATION OF DATA ON 35-mm FILM

Images of weather data are created in shades of gray on a microfilm plotter. A Fortran program was written to read the Climate Dynamics tape, convert the data for use in the Integrated Graphics System (IGS) subroutines, and create the plotting commands for the microfilm plotter. The data on the Climate Dynamics tape are in a 72×46 matrix for each climatic variable where each element in the matrix contains a value for that variable over a map area of 5° by 4° .

Figure 5 is a schematic of a frame generated by that program using calls to the IGS subroutines MLTPLG and LEGNDG. The map consists of 72 pixels (or picture elements), 40 rasters on a side in the x direction, and 46 pixels, 32 rasters on a side on the y direction. This preserves the 4 to 5 ratio of the original data. The upper left corner contains the experiment number and the map label. In this schematic, a ten-step gray scale is shown, but the program allows a variable number of gray levels. The grays that are used to generate a particular image appear in the gray scale accompanying it.

The data for a gray map can be distributed among the contour intervals in two ways. One method is to divide the range of the variable into as many intervals as desired, establish which interval each of the elements of the 46×72 -matrix falls into, and plot the corresponding picture element with the related shade of gray. The other method is to count the number of elements which fall into each interval, integrate the curve of these data and normalize it. If the chosen number of intervals happened to be 10, a curve such as shown in Fig. 6 would result. The contour intervals are then chosen to contain a cumulative percentage of the data, with 10 percent of the data in the first interval, 20 percent in the second, etc., with the grays increasing in intensity.

The gray shades are created by plotting lines or vectors within the pixels, using the IGS subroutine MLTPLG, as shown in Fig. 7. Each darker gray contains more vectors than the preceding one.

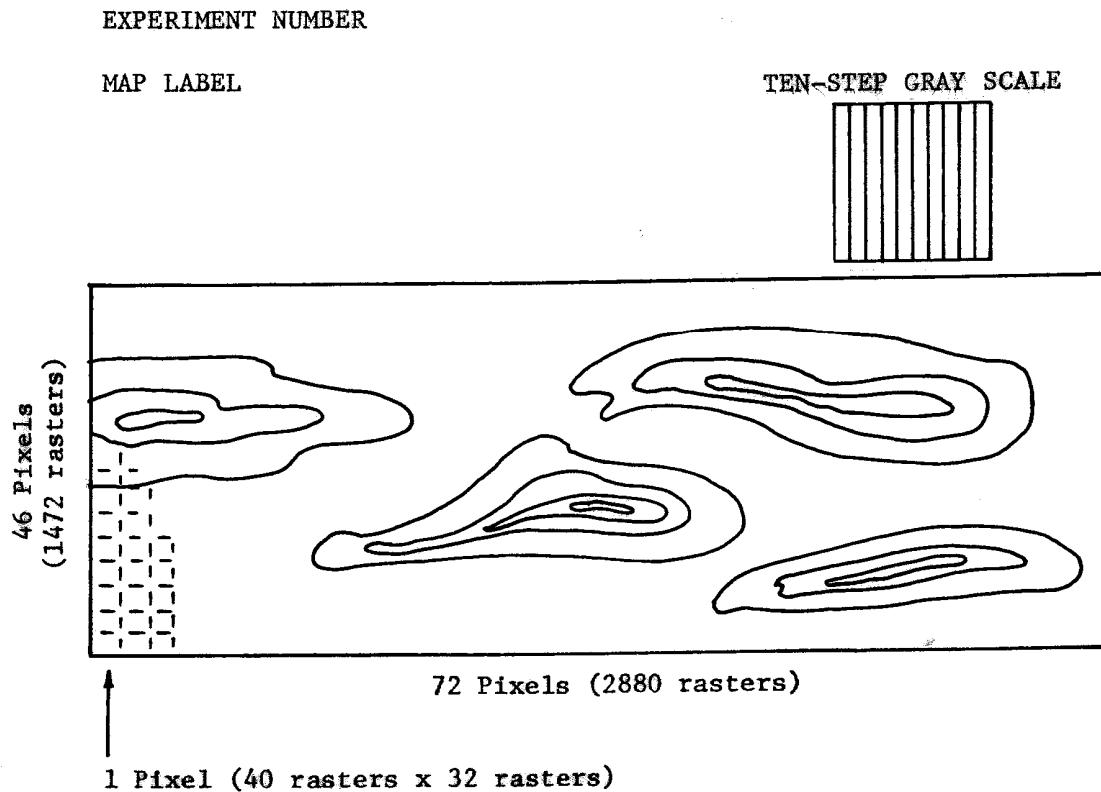


Fig. 5 — Schematic of IGS frame

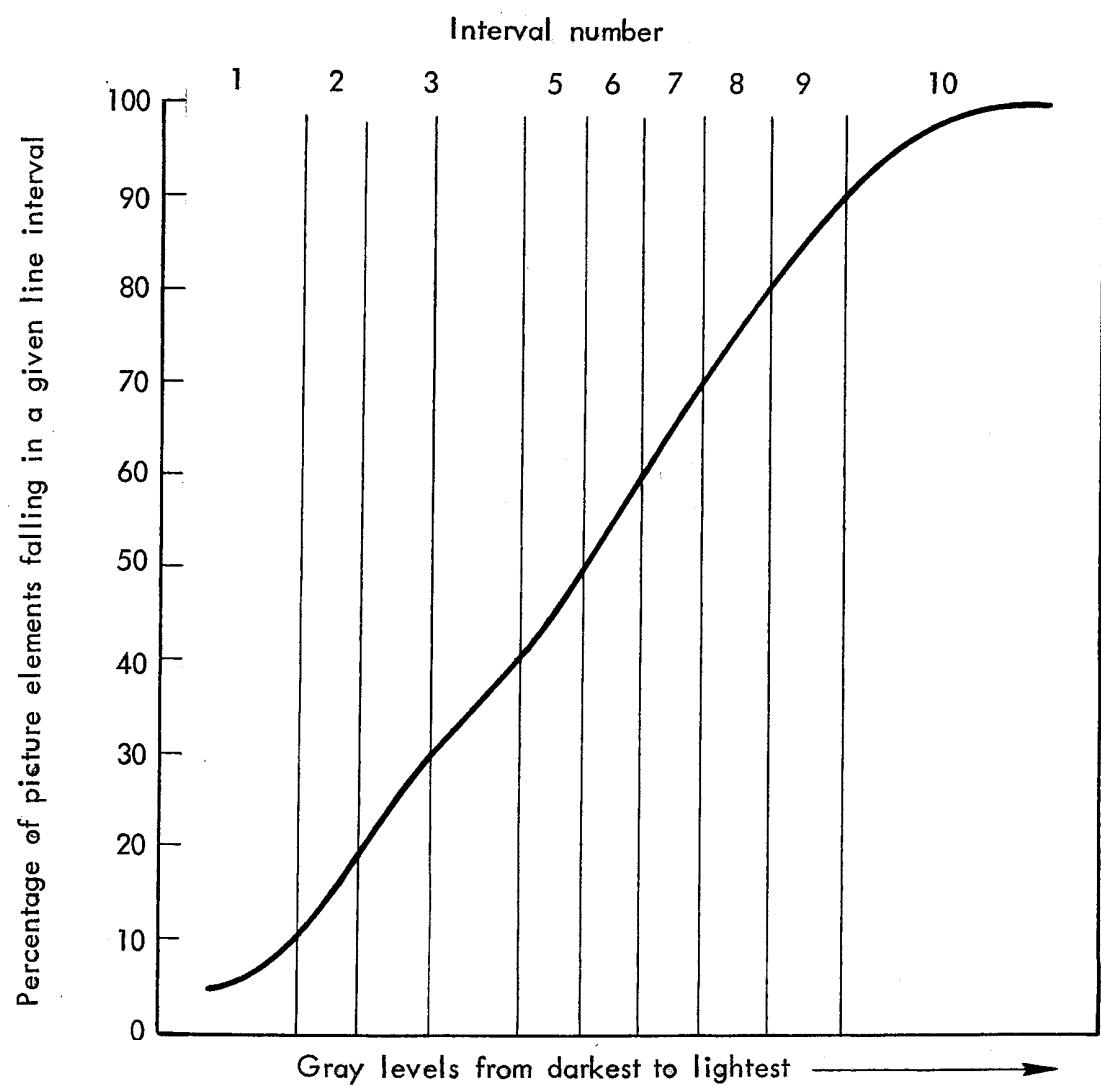
MLTPLG's arguments are the x,y coordinates of the vectors defining the edge of the pixel, and the number of vectors to plot between those edges. If the number of available plotting locations between the two defined vectors is less than the number of lines called for in the argument, IGS calculates which lines should be overstruck to ensure that all the required lines are plotted.

The image is created on pixel at a time until the entire map is formed. The gray scale in the upper right corner is generated in much the same way and displays the grays used in the image. Lastly, the legends are generated with LEGNDG.

Inputs to the program are the map number, the surface to be depicted (some of the maps are calculated for conditions above

Minimum of values = 0.0
Maximum of values = .9875

Interval value = each 10% of data
Variable: Total cloudiness



Cumulative percentage of picture elements falling into each contour interval

Fig. 6 — Contour intervals for gray maps

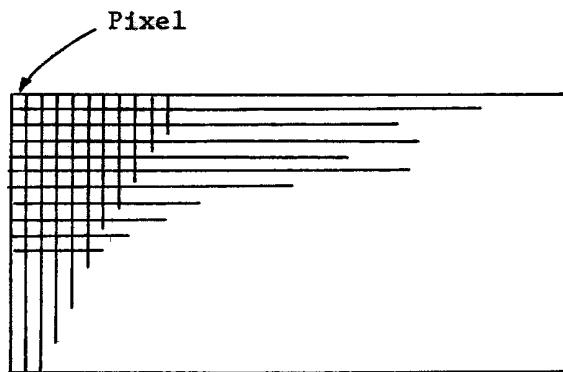
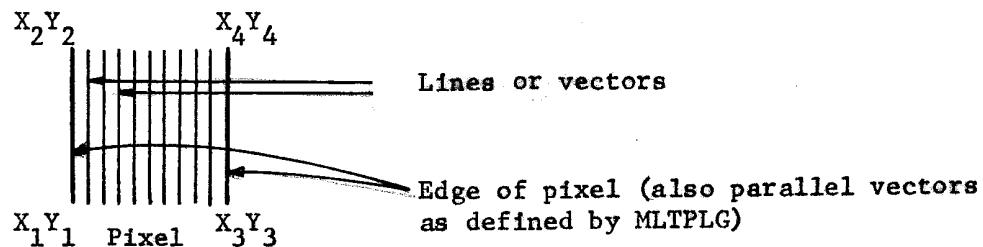


Image (composed of 46x72 pixels)



Call MLTPLG(Z, No. Lines, X_1 , Y_1 , X_2 , Y_2 , X_3 , Y_3 , X_4 , Y_4)

(In this example No. of Lines = 9)

Fig.7 — Shade generation by MLTPLG

the earth's surface), the number of contour intervals, the direction of the gray scale (whether the high values of the data are to be dark, or the low), the number of lines to be plotted in the basic pixel, and the increment by which to change the basic pixel.

The program searches the climate dynamics tape for the map and surface requested and brings in the 72×46 matrix of those values. It then finds the maximum and minimum of the data, and divides this range into the appropriate contour intervals, and creates a new matrix.

For example, assume that the desired number of contour intervals is 10. The program tests the input matrix against the range in each of the contour intervals and assigns a value of 1 through 10 to a new 72×46 -integer matrix, depending on the interval into which the data fall. This matrix then contains the level of gray to plot in each pixel relative to the input data.

Subsequently, a one-dimensional matrix of the number of vectors to be plotted in each pixel is calculated from the inputs. The number of vectors to be plotted in the basic pixel, whether it is to be the lightest or the darkest shade, appears as the first element. Each succeeding element is calculated using the basic pixel plus an increment. Generally, ten contour intervals have been satisfactory for images which are not to be transformed into color, with the lightest shade containing five vectors and the darkest fifteen. The lightest shade contains five vectors in order to create the appearance of a smooth gray shade within the pixel instead of a series of individual lines.

The next step is to test the integer matrix, starting at the lower left corner, holding the y constant, and incrementing the x. If the matrix contains a one, the first value of the table of vectors becomes the number of vectors to plot in the picture element; if the integer matrix contains a two, the second value in the vector table becomes the number of vectors to plot, etc. For each element of the integer matrix, a call to MLTPLG is made, creating the input to the microfilm plotter for generating the image. Figures 8 and 9 are pictures made from frames generated by this technique. Figure 8 is a map of total precipitation with the light areas the least precipitation and the dark areas the most precipitation. Figure 9 is a map of total cloudiness, the same variable as shown in Fig. 2, with the darkest areas the heaviest cloud cover. In comparing these two figures, it is obvious that Fig. 9 gives a better instant grasp of the overall global cloudiness conditions.

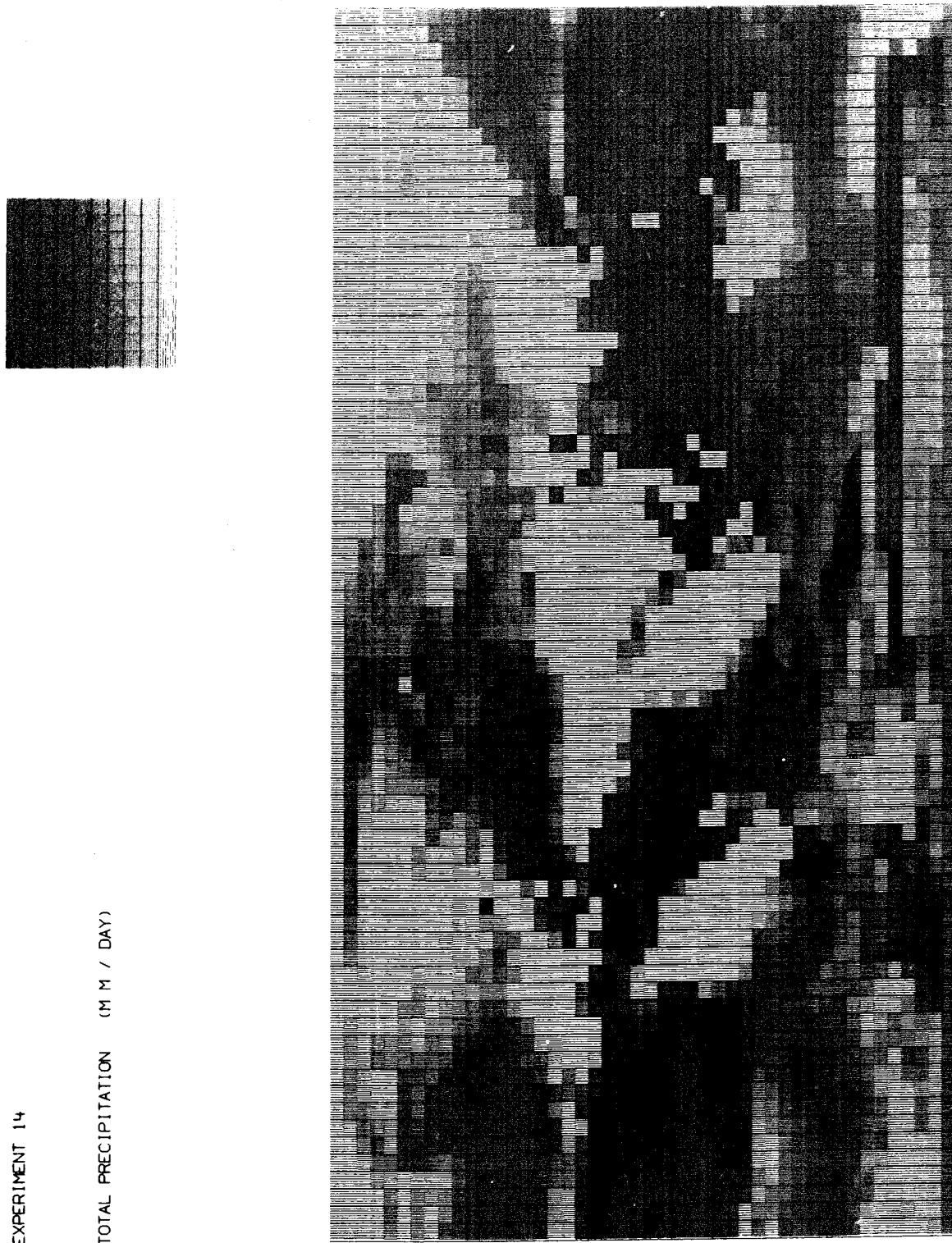


Fig. 8 — Gray scale map of total precipitation

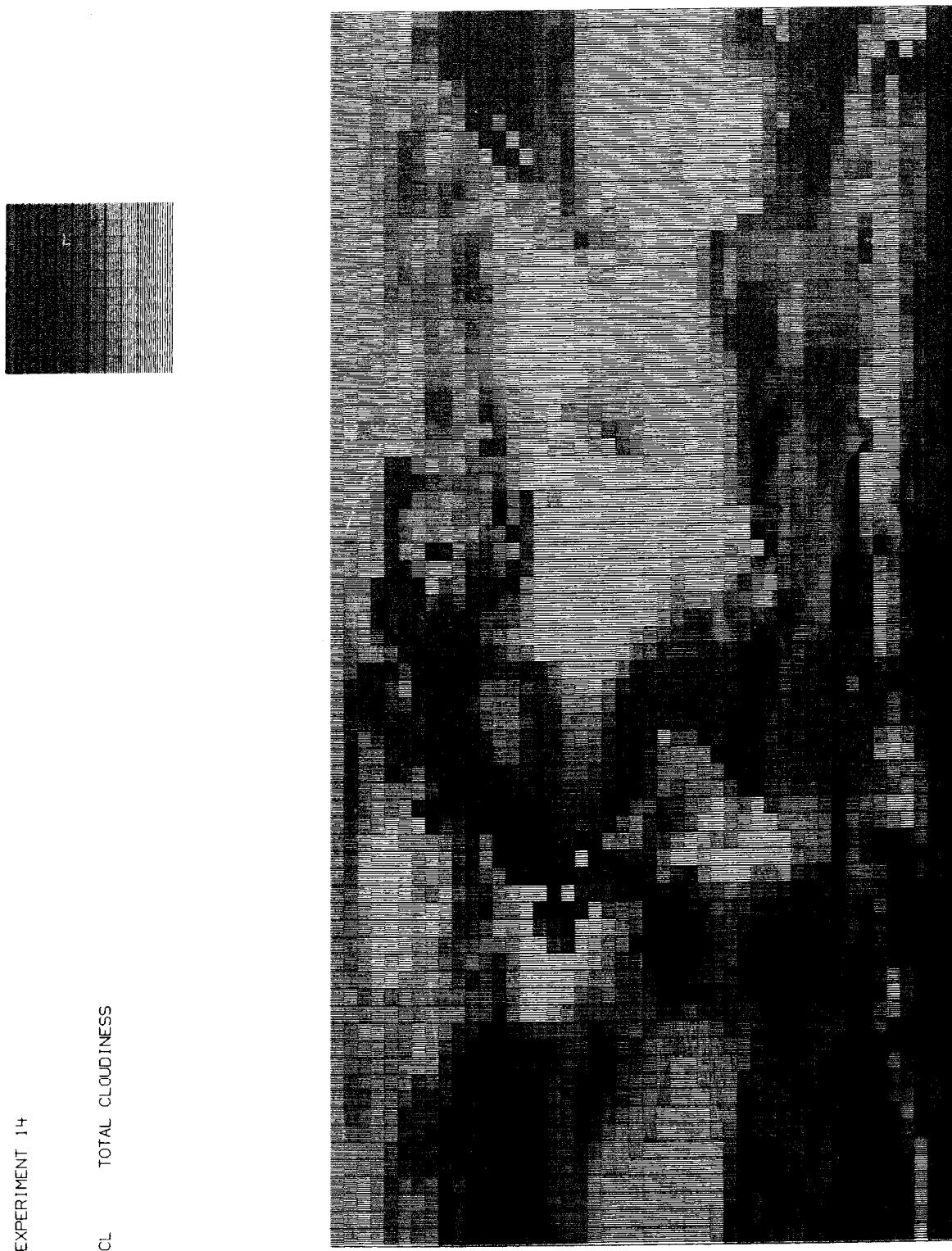


Fig. 9.—Gray scale map of total cloudiness

The pixels are created in the x direction, and each time one is generated, the edge of the preceding one becomes the edge of the present one, thus overstrikes occur along these edges. To alleviate the overstrike problem, each pixel is defined as 40 rasters wide, but when the call to MLTPLG is made, the vector defining the leading edge of the pixel is indented 1 raster location. This does not get rid of the heavy lines between pixels, but it makes the condition less distinct.

PRESENTATION OF DATA IN A COLOR FORMAT

After the black-and-white 35-mm film images are generated from digital weather data, the imagery is color-coded. This can be done by additive projection, photographic transformation, or color television. Other systems exist but are not discussed here.

Additive projection offers a rapid method of combining two images for observation with the ability to change the chromaticities (colors) of the primaries (red, blue, green) in a relatively short time. We have used a standard incandescent $3\frac{1}{4} \times 4$ lantern slide projector with a modified slide carrier for 35-mm film strip. The carrier has two adjacent windows which may be fitted with various Wratten filters to provide the two primary colors. Images are superposed by a right-angle projection onto either an opaque white surface or a rear-projection material by using a folding mirror in each light path. With two-color additive projection, the resulting color of any portion of the image always lies on the line connecting the chromaticities of the two primaries on the CIE diagram; ⁽⁸⁾ this is illustrated in Fig. 10. In the case of pseudocolor, we are using only one parameter (such as temperature or precipitation) and the color display is accomplished by simultaneous projection of a positive and negative of the same image, each with a different primary color. With false color, the positive (or negative) images of both parameters (such as temperature and precipitation) are projected simultaneously with different primaries. By the colorimetry of additive projection, we can quite accurately determine the color gamut (straight line) on the CIE diagram for any set of primaries. The work of MacAdam ⁽¹⁰⁾ indicates that the selection of primaries in a two-color additive system will not necessarily yield

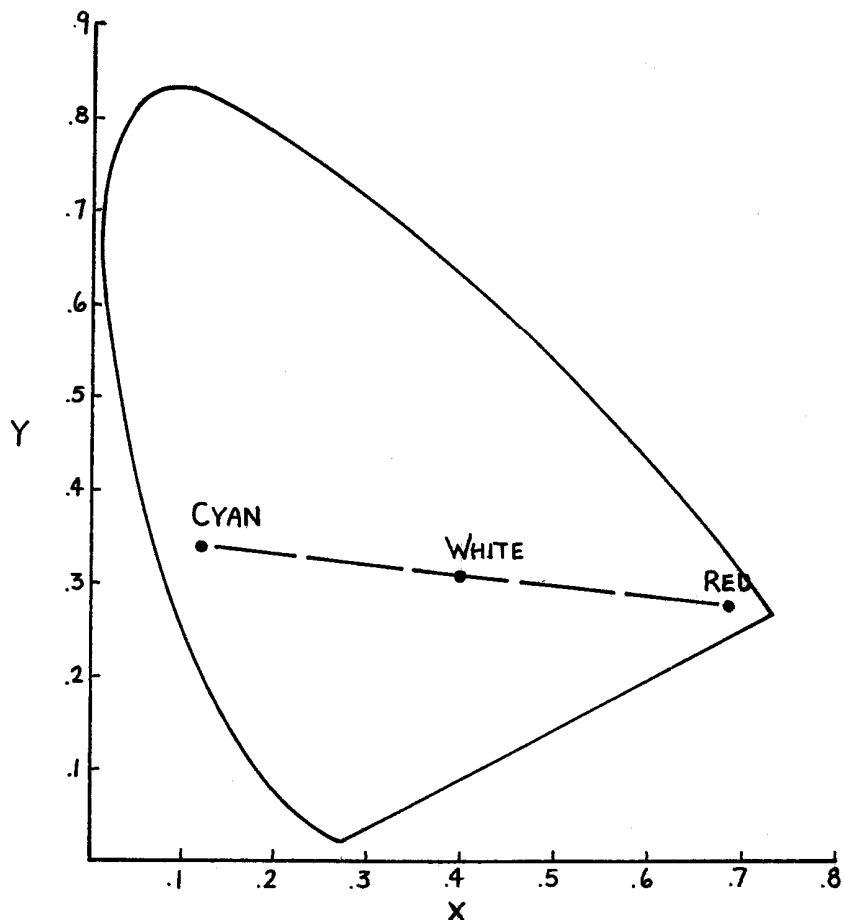


Fig. 10 — Color gamut on the CIE chromaticity diagram of a two-color additive system. All possible colors produced by mixing varying amounts of red (R) and cyan (C) primaries lie on the dotted line. An explanation of the X and Y coordinates is given in Ref. 7

a straight-line gamut which intersects the achromatic axis, and at the same time provide the maximum number of discriminable color steps. This means that, for maximum color discrimination, the image might not contain any neutral grays. Also, what is "neutral" depends largely upon the type of light source in the projection device; a tungsten light source is much more yellow than a xenon source, but the eye adapts

both of them to "white" if they are not seen side by side. We are therefore faced with a tradeoff between minimum color saturation and maximum discrimination; experimentation, using the observations of meteorologists, will determine an optimum compromise in the selection of the primaries.

Good image registration is essential for all additive systems. Our present system distorts both images very slightly in opposite directions because of the off-axis windows in the carrier, but the distortion drops rapidly as projection distance is increased; this condition could be eliminated completely by use of two sets of projection optics at right angles and a beamsplitter with no folding mirrors.

Photographic techniques for producing pseudocolor transformations were developed at Rand a few years ago. One such process uses only two black-and-white intermediate separations, but at the same time produces a color gamut which includes all the spectral hues at fairly high saturation; ⁽⁴⁾ this is accomplished by taking advantage of the nonlinear responses of the dye layers in photographic color materials, and cannot be duplicated with two-color additive projection. The color gamut of the two-separation process is shown in Fig. 11. False-color images may also be produced photographically by successive exposure of black-and-white images of two different parameters onto color material with light sources of different colors. The appearance of the final color image depends on the density range of the black-and-white images, the spectral composition of the light sources, and the amount of exposure to each. Color displays that are produced by additive projection, as we have discussed, can be approximately equaled by photographic procedures, with somewhat less control of colorimetry.

Closed-circuit color television offers some interesting possibilities for pseudocolor imagery. The Graficolor System, manufactured by Spatial Data Systems, is available at Rand; it is presently being used in a program for the partially sighted. This system was designed primarily for the textile industry, but lends itself to pseudocolor transformations. It consists of a black-and-white camera, a color monitor, and an intermediate "black box" which divides the original black-and-white image viewed by the camera into ten discrete density

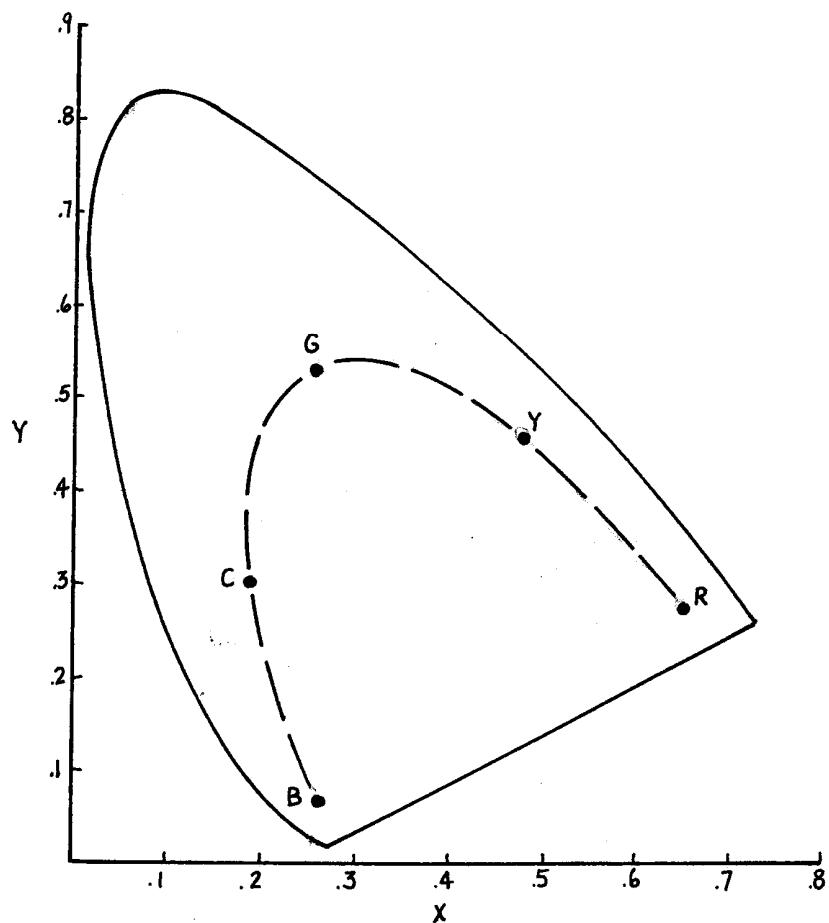


Fig. 11—Color gamut (dotted line) obtainable with two-separation process described in text. Spectral hues include red, yellow, green, cyan, and blue. This differs from a two-color additive system in that the gamut is not limited to a straight line. An explanation of the X and Y coordinates is given in Ref. 7

steps and displays each step as different color on the monitor. The color of each step may be determined separately by the operator by selection of the amounts of each of the red-, green-, and blue-color primaries for each density level in the original. The versatility of this system is great, as there are 4,096 possible chromaticities for each of the ten density levels. It is doubtful whether our TV system

could be used effectively for false-color displays involving two black-and-white images; this would require an image storage capability which it currently does not have.

Of course, there are pros and cons to the three display techniques we have discussed. Additive projection offers flexibility in changing primaries and imagery, but without the retention of a permanent image. Photographic techniques offer a permanent image but require chemical processing steps. Television systems offer versatility and could retain permanent images with adequate storage capability, but image quality is comparatively degraded. We intend to use additive projection to determine the most nearly optimum type of color enhancements from many images, image combinations, and selection of primaries; the most promising of these will then be duplicated photographically for permanence.

IV. CONCLUDING REMARKS

As to the present status of our work, some of the techniques we have described have been tried with various degrees of success; in general, the results look encouraging. In addition to creation of false-color images with the two-color additive projection scheme, we have generated three false-color images photographically, using temperature-precipitation, evaporation-cloudiness, and evaporation-precipitation as variables. These images were produced directly from the 35mm black-and-white computer output by in-register successive projection onto 8 × 10 Ektacolor Print Film, using gelatin filters to provide the necessary primaries. As an example, one of the combinations is the evaporation variable printed with a red light source, and the cloudiness variable printed with a blue-and-green source. A schematic of the color scale accompanying this image is shown in Fig. 12. In this combination there will be a band of red in the image, centered about the equator, denoting low cloudiness and high evaporation, a band of yellow, both north and south of the equator, denoting high evaporation and heavy clouds, and a band of green, near the Arctic and Antarctic Circles, denoting low evaporation and heavy clouds. The continents are discernible because of low evaporation and low cloudiness, and thus appear as a dark brown.

We are investigating methods of increasing the range of the grays in the images and also ways of creating a more even shade of gray within a pixel. The first images we created contained 10 discrete density steps, which seems to be adequate for gray images, but with the construction of the color images, 100 discrete density steps appear, which may be too many except for general pattern recognition. We intend to investigate creating the colored images with 9, 16, or 25 discrete color steps, thus creating a simpler image, but still one containing a significant amount of data.

Some minor improvements are planned for the additive projection system, such as modification of the film-strip carrier to accept

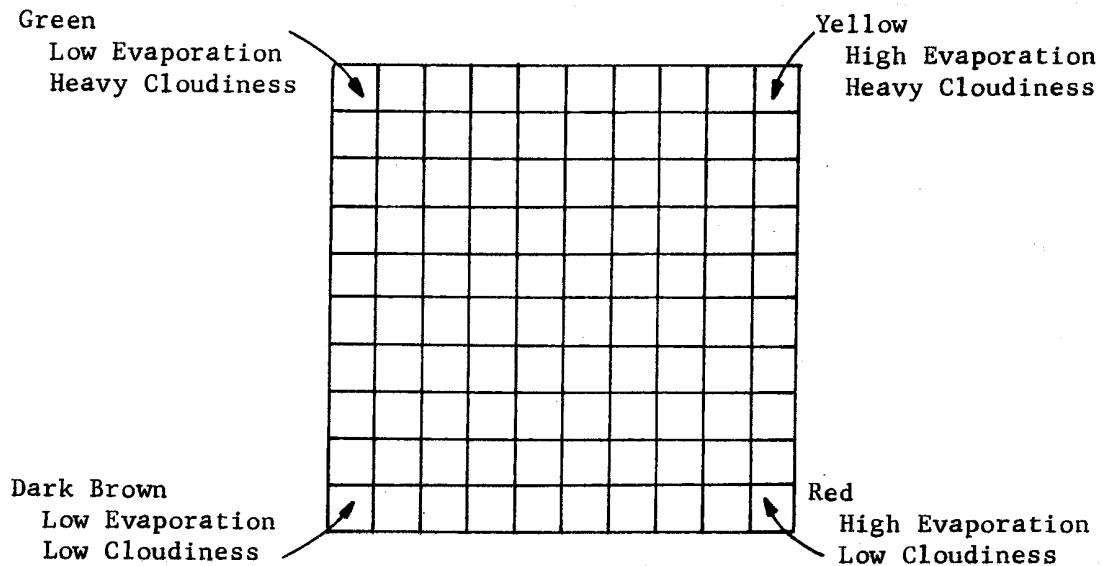


Fig. 12--Schematic of color scale for cloudiness-evaporation

additional neutral-density filters in order to be able to balance the amounts of the primaries more rapidly, and a vernier adjustment of one folding mirror to facilitate image registration. Photographic techniques for the production of color imagery have previously been developed at Rand and need only minor modifications, if any, for application to the display of weather data. The Graficolor closed-circuit television system available at Rand needs no modification for the presentation of pseudocolor imagery from our 35-mm filmstrips; this system will be used when applicable, along with the additive projection and photographic techniques.

The authors' past experience has shown that quantitative evaluation of image-enhancement techniques is difficult, and therefore evaluation depends largely upon the qualitative opinions of observers familiar with the particular type of imagery under consideration. For climate-related imagery, the several meteorologists on the Rand staff can provide meaningful feedback in our further development of display technologies. More specifically, the present methods of weather-data

interpretation must be compared with various types of color displays with respect to interpretation rapidity, accuracy, and improvement with repeated exposure to imagery of the same general type.

Several of Rand's meteorologists have viewed both the additive projection images and the photographically produced images. The consensus is that they are a new and unique way of presenting meteorological data and deserve more thorough investigation. We hope to proceed by producing a set of test images, and then presenting them to experienced observers for evaluation.

Should the results of these evaluations indicate that the interpretation of meteorological data can be significantly improved by the use of pseudocolor and false-color displays, we will investigate the feasibility of automation of display systems using such techniques.

NOTE: The expense of including color reproductions of the imagery we have produced precludes their inclusion in this report; the original color plates remain in the possession of the authors.

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